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# Experimental investigation of blast wave propagation in an urban environment

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## Abstract

Lab-scale experimental investigations on blast wave propagation in a complex environment are proposed in this paper. Studies of blast propagation are described in the literature, but only a few studies at lab-scale were found while this scale option represents an economic and safe approach.

Five experimental configurations, built with wood boxes on a 2.8 m wood table, are tested in a 1:200 reduced scale using three types of explosives. Several characteristics of the explosives are given: the geometry of the explosion, the repeatability, and the TNT equivalent.

An overview of impacts of a complex environment on the blast wave characteristics is proposed. The urban configurations investigated are the straight street, the T-junction, the cross junction, and the channeling. Investigations on reduced-scale effects on blast measurement and characteristics are detailed.

## Introduction

As long as explosives represent a threat, understanding the explosion mechanism and its consequences in cities will remain an important issue. Examples of tragedies caused by explosions are numerous. The Oklahoma terrorist attack, United States, 1995, is one of them. A truck filled with handmade explosive exploded, heavily damaging the Alfred P. Murrah Federal Building. The effect of the blast created was equivalent to an explosion of more than 2300 kg of TNT and caused 168 deaths and more than 500 injured [1]. A more recent example is the accident of the west fertilizer company explosion, West Texas, 2013. A charge of more than 28 tons of ammonium nitrate detonated in a storage, causing 15 deaths, more than 200 injured and around 100 MUSD of damages [2][3].

Two main characteristics are used to describe a blast: the overpressure peak and the positive impulse, defined as the integral of the pressure time signal from the start of the blast and the end of the positive pressure phase (Figure 1).

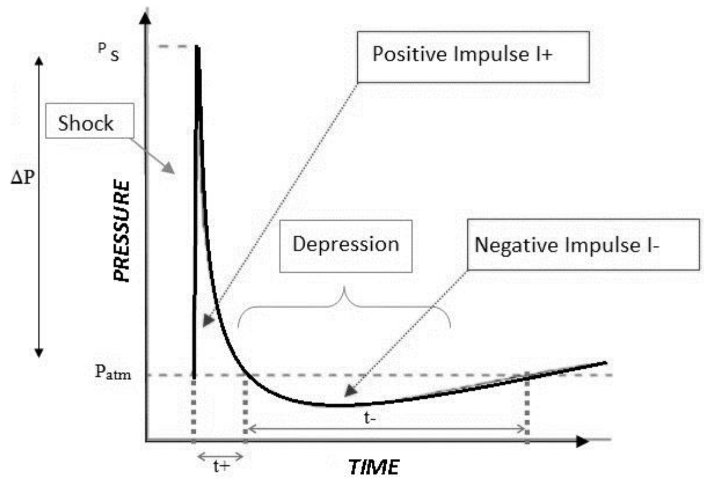

Figure 1: General shape of a blast wave *(ΔP: overpressure peak, Ps: maximal pressure of the shock, Patm: atmospheric pressure, t+: duration of the positive phase)*

The most common configurations studied in the literature are the straight street, the T-junction, and the cross junction. These configurations have been studied by A. Dörr *et al.*[4] using a charge of 15.6 g of PETN to simulate a 1000 kg vehicle bomb explosion at a 1:40 scale. It was concluded that the overpressure was increased in a straight street compared to a free-field propagation and reduced in presence of gaps between buildings. The T-junction and cross junction have similar effects: the blast wave is attenuated by the street separations.

The influence of the width and height of the street has been more deeply investigated by T.Rose *et al.* [5]. The experiments modeled a charge of 1000 kg of TNT using a 1:40 model scale and a charge of 11.09 g of DEMEX 100 plastic explosive. The observations of A.Dörr *et al.* [4] have been confirmed regarding the increase of the blast wave characteristics in straight streets. Moreover, T.Rose *et al.* [5] have also concluded that the observed overpressure increases with the building height until a limit height. Buildings higher than 3.2 m/kg$^{1/3}$ can be assumed infinitely high: higher constructions will not further affect the blast wave propagation.
Smith *et al.* [6] [7] investigated the channeling effect by means of 1:40th scale experiments and 3D numerical simulations. Several parallel lines of buildings and regular arrays of detached houses were investigated. The authors concluded that the presence of buildings between the explosive and the measuring location reduced the blast load, whatever the obstacles configuration. Moreover, the blast reducing effects of shielding are offset by the blast enhancing effects of channeling in a complex array of identical buildings.

Although research has been performed on the blast propagation in free-field and complex environments, this knowledge remains incomplete. The studies summarized above relate to a medium scale factor. However, studies in laboratory scale are difficult to find. The objective of the study is, therefore, to go further in the understanding of the impact of obstacles on the blast propagation by conducting experiments in lab-scale.

Experimental campaigns have been performed in a 1:200 scale in order to compare different configurations of obstacles. Variations of characteristics (overpressure peak and positive impulse) of a blast propagating inside the different configurations are detailed and compared. The effects of the straight street, the height of obstacles, the T-junction, the cross junction, and the channeling are investigated.

A common approach to transpose characteristics of a blast to another scale is the use of the Hopkinson scaling law [8]. In this study, the Hopkinson law is described and investigated for different obstacles configurations using experimental data from two detonators composed by different masses of a same explosive compound.

## Materials and Methods

The experimental campaign has been conducted at the von Karman Institute. The set-up has been designed to conduct non-destructive studies of blast wave propagation in urban environments.

Tests are conducted in a room of approximately 5 x 10 x 6 m, which allows an assumption of a free-field propagation. Experiments are performed on a 2.8 m diameter wood table. For each test, the explosive is placed in the center of the table. A metal plate of 55 x 55 cm replaces the wood in the middle of the table for better protection against the explosion.

The effect of the explosive source is studied through the use of three types of explosives: two detonators and one firecracker. The firecrackers used are cylinders of 53 mm height with a diameter of 17 mm. The composition is assumed to be black powder. The detonators are metal cylinders filled with 70 mg of PETN as initiating explosive and 123 mg and 1031 mg of RDX as output explosive, respectively for the RP80 and RP83. The explosive charges are stored in an aluminum cup with a plastic molded head. The characteristics of each explosive are gathered in Table 1. The TNT equivalents have been estimated from free-field tests conducted at the von Karman Institute and are given as a ratio and a mass of TNT equivalent [9].

Table 1 : Characteristics of explosives used (TNT equivalent estimated)

| Explosive | Constructor | Diameter | Composition | TNT eq [9] | |
|---|---|---|---|---|---|
| Firecracker | Nitrate banger C20 | 17 mm | 1.4 g | 0.96 | 1.34 g |
| RP-80 EBW detonator | RISI | 5.6 mm | 0.08 g PETN<br>0.123 g RDX | 1.10 | 0.136 g |
| RP-83 EBW detonator | RISI | 7.1 mm | 0.08 g PETN<br>1.031 g RDX | 1.27 | 1.31 g |

During tests, firecrackers are taped directly on the center of the test table and lighted manually with a lighter. Detonators are set inside a solid foam block of 5 x 5 cm in the center of the table, standing out of the experimental table from a given height (9 mm for the RP80; 25 mm for the RP83). They are activated using a FM150 firing module and a FD201 firing system.

The test table is perforated with 1 cm diameter holes to mount sensors flush to the surface. Ten flush mounted sensors are used to record the blast: seven piezoresistive transducers (five PCB 116 and two Kistler 603B) and three piezoelectric transducers (two Kistler 4043A5, one Kistler 4043A2). Each sensor is statically and dynamically calibrated with its measurement chain (amplifier and cables). More information about the sensor characteristics can be found in [9]. The pressure variation of all sensors is recorded with a sampling frequency of 8 MHz, using a NI PXIe-7962R system with a NI-5751 acquisition module. The sample size is equal to $40.10^6$ points per channel. The sensors are screwed in aluminum cylinders fixed to the test table using an elastic system, depicted in Figure 2. This experimental setup has been selected as optimum for blast wave measurement and minimizes the influence of external perturbations on the measurement [9].

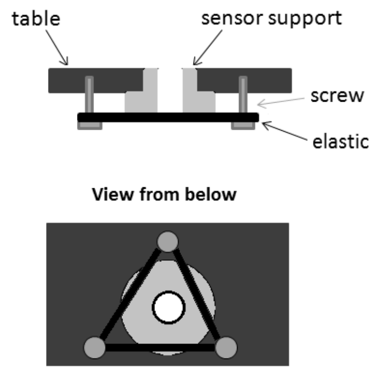


Figure 2: Sensor fixation

The effects of the obstacles configurations on the blast propagation are studied through six experimental configurations. Each configuration is built with 1 cm thick wood boxes. If not specified, the obstacles height is equal to 10 cm. The configurations, depicted in Figure 3, are:

1- The free-field, with no obstacles;
2- The 10 cm width straight street;
3- The 10 cm width straight street with buildings of 20 cm height;
4- Part A: The 25 cm width straight street;
Part B: The 25 cm width T-junction.

*The part A and B are supposed independent concerning the propagation of the incident blast wave;*

5- The cross junction, with a 10 cm width street and 25 cm width street;
6- The channeling, built with 15 cm x 10 cm wood boxes, separated from each other by 5 cm.

The position of the explosive and sensors are respectively indicated by a circle and crosses in Figure 3. The exact positions of the sensors are summarized in Table 2.

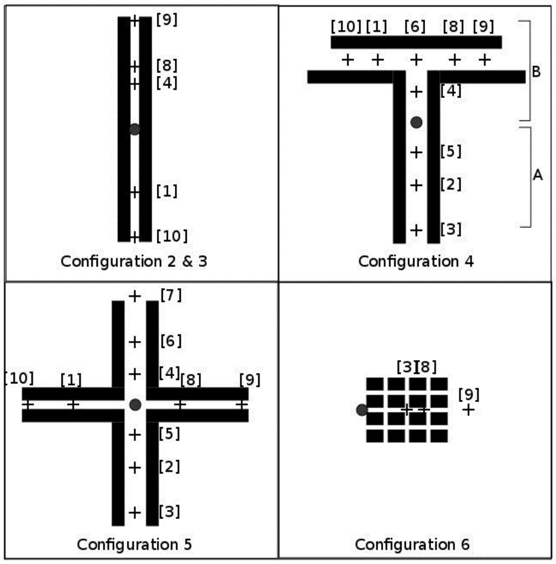


Figure 3 : Configurations tested (configuration 1: Free-field)

Table 2 : Positions of sensors for each configuration *(the position .../s6 represents the distance from the sensor 6)*

| Sensor | Number | Conf. 1 | Conf. 2 and 3 | Conf. 4 | Conf. 5 | Conf. 6 |
|---|---|---|---|---|---|---|
| PCB 106 | 1 | 475 mm | 725 mm | 450 mm/s6 | 725 mm | |
| PCB 106 | 2 | 725 mm | | 725 mm | 725 mm | |
| PCB 106 | 3 | 725 mm | | 1250 mm | 1250 mm | 525 mm |
| Kistler 603B (1) | 4 | 350 mm | 525 mm | 350 mm | 350 mm | |
| Kistler 603B (2) | 5 | 350 mm | | 350 mm | 350 mm | |
| PCB 106 | 6 | 725 mm | | 725 mm | 725 mm | |
| PCB 106 | 7 | 725 mm | | 800 mm/s6 | 1250 mm | |
| Kistler 4043A5 | 8 | 975 mm | 725 mm | 450 mm/s6 | 525 mm | 725 mm |
| Kistler 4043A5 | 9 | 1079.8 mm | 1250 mm | 800 mm/s6 | 1250 mm | 1250 mm |
| Kistler 4043A2 | 10 | 1225 mm | 1250 mm | 1250 mm | 1250 mm | |

Table 3 gathers the dimensions of the configurations scaled by TNT mass equivalent cubic root of each detonator.

Table 3: Scaled dimensions of the configurations 2, 3 and 4-Part A (m/kg$^{1/3}$) for the two detonators

| Explosive | Conf. 4 Part A | Conf. 2 | Conf. 3 |
|---|---|---|---|

| | width (25cm) | height (10cm) | width (10cm) | height (10cm) | width (10cm) | height (20cm) |
|---|---|---|---|---|---|---|
| RP80 | 4.86 | 1.94 | 1.94 | 1.94 | 1.94 | 3.89 |
| RP83 | 2.28 | 0.91 | 0.91 | 0.91 | 0.91 | 1.83 |

The configurations 1, 2, 3 and 4 have been tested with the three types of explosive. The other configurations have only been tested with the firecracker and the RP80 detonator. In total, 24 tests have been conducted (Table 4).

Table 4: Experimental Matrix

| Configurations | Firecracker | RP80 | Rp83 |
|---|---|---|---|
| Configuration 1 | 4 | 2 | 2 |
| Configuration 2 | 1 | 1 | 1 |
| Configuration 3 | 2 | 1 | 1 |
| Configuration 4 | 2 | 1 | 1 |
| Configuration 5 | 1 | 1 | - |
| Configuration 6 | 2 | 1 | - |

In order to study the effect of the obstacles on the blast propagation, the positive impulse and the overpressure peak of the blast are compared between different configurations.

## Result and Discussion

### Free-field

Free-field experiments have been conducted to study the repeatability, the geometry and the TNT equivalent of each explosive.

A good repeatability and circularity of explosions have been observed for the detonators [9]. The explosion of the firecracker presents a non-circularity with a random predominant direction. This difference of repeatability between detonators and firecrackers can be explained by the high quality of fabrication and ignition of the detonators, while firecrackers are not always exactly identical and present a weakness point that leads in a random energy release direction.

Figure 4 presents the variation of the overpressure and the scaled impulse regarding the scaled distance for the three explosives. All the values have been scaled using the TNT mass equivalent obtained experimentally [9]. A good fitting with the references curves from the Kinney theory [8] and the GEMO studies [10] is observed. The impulse presents better reliability as the overpressure depends on sensor characteristics like response time or resonance frequency.

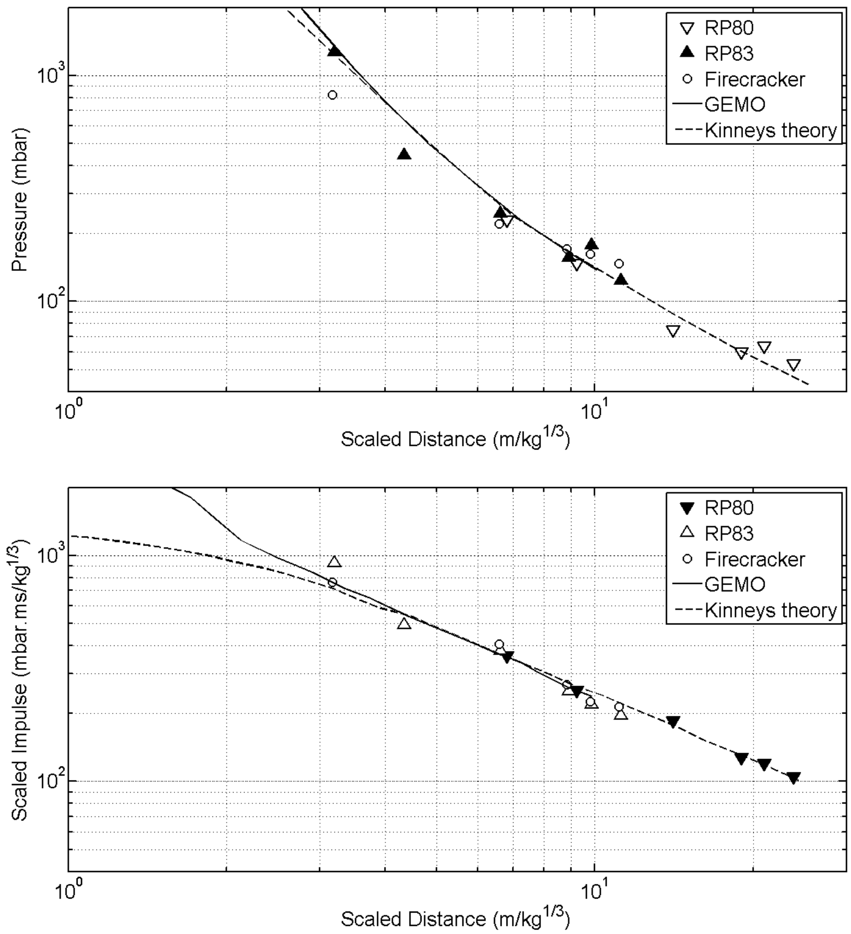


Figure 4 : Variation of the overpressure peak and the scaled impulse regarding the scaled distance for the three explosives

The firecracker shows a bad repeatability compared to detonators. However, similarities between the characteristics of blasts from firecrackers and detonators can be observed. Moreover, firecrackers induce less vibration on the test table and less electronic noise, which make the post-processing easier [9]. It is then advised to use firecrackers in order to conduct preliminary tests and qualitative studies of the phenomenon studied. Thereafter, tests can be conducted with detonators to perform quantitative analysis.
The impulse study shows a better reliability than the pressure peaks study, as it depends less on the response of the sensor. It is then advised to prefer to use the impulse characteristic for quantitative studies.

## Straight Street

The straight street effect on the blast propagation is studied through the comparison of the characteristics (positive impulse and overpressure peak) of a blast propagating in free-field, inside a 25 cm straight street and inside a 10 cm straight street (configurations 1, 2 and 4-Part A, cf. Figure 3).

Figure 5 depicts the variation of the scaled characteristics of blasts generated by RP83 detonators propagating in the three studied configurations. A general increase of the characteristics is observed when the width of the street decreases. However, the blast at 350 mm from the explosion inside the 25 cm straight street (first left circle point on the overpressure graph) presents the same pressure than a blast propagating in free-field. Two blast waves are propagating inside the straight street: the incident blast and the blast reflected on the walls of the street. At 350 mm from the center of the explosion, the reflected blast did not merge yet with the incident one. The signals of blasts propagating in free-field and in the 25 cm straight street are superposed in Figure 6 using the time of the impulse from the firing system as the initial time of the explosion. Two peaks are visible on the 25 cm straight street blast and correspond to the incident and reflected blasts. The first peak is equal to the blast in free-field, from the pressure variation and the speed of propagation. The reflected blast propagates faster than the incident one, merges with it at a given distance and induces the increase of the blast characteristics.

Concerning the variation of the impulse, presented in Figure 5, the positive impulse decreases faster when the street width is smaller. This observation was also made by T. Rose *et al.* [5] by investigating the propagation of a blast from a 11.09 g of DEMEX 100 plastic explosive inside different configurations of straight streets using sensors on the walls of the buildings. The experimental results from the two closest configurations to the configurations studied in this paper have been superposed to the experimental variation of the positive impulse in Figure 5. They correspond to straight streets of 1.6 $m/kg^{1/3}$ and 2.4 $m/kg^{1/3}$, built with 0.8 $m/kg^{1/3}$ high buildings. The experimental data and the T.Rose’s data are different due to the different position of the sensors (wall of the buildings vs. flush at the ground) and the difference of configuration dimensions. However, a similarity of decrease is observed far from the center of the explosion.

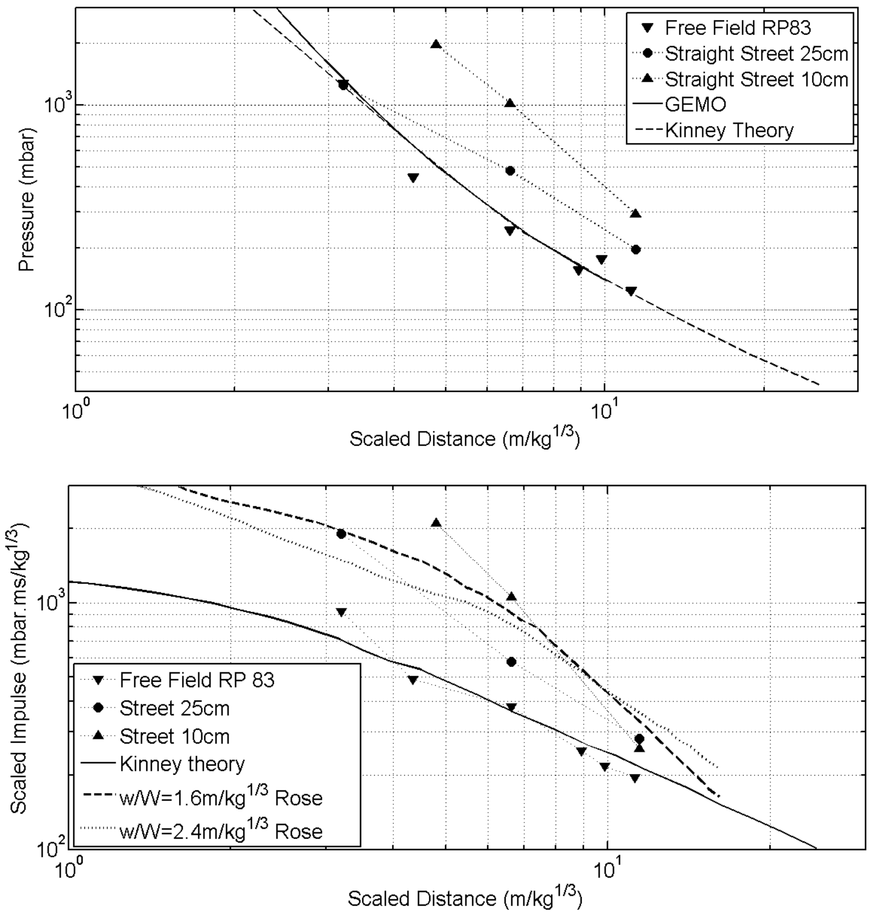


Figure 5: Impact of the street width on the scaled characteristics variation of a blast produced by a RP83 regarding the scaled distance (up: overpressure peak, down scaled positive impulse)

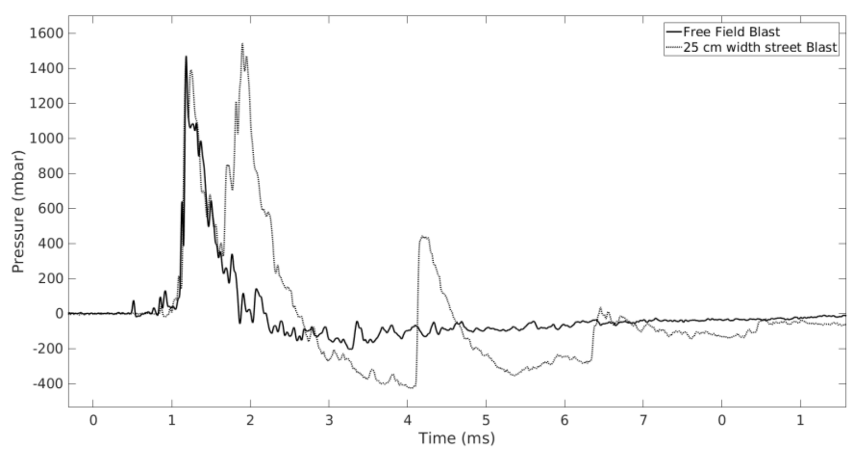


Figure 6: Pressure signal of a blast at 350 mm from the explosion of a RP83 in a 25cm width street and in free-field (signals from C4, 200 kHz filtered)

Figure 7 depicts the variation of characteristics of the blast generated by a RP80 detonator and propagating inside the configurations 1, 2 and 4-Part A. As for a blast generated by a RP83 detonator, the characteristics are increased by the confinement of the straight street. As the pressure induced by a RP80 detonator is lower than the one generated by a RP83 detonator, the reflected blast takes more time to merge with the incident one. At 350 mm from the center of the explosion, the positive phase of the incident and the reflected blasts are totally distinct, as shown in Figure 8. As a consequence, the positive impulse of the first incident blast corresponds to the positive impulse of a blast propagating in free-field, as depicted by the "incident blast" marker on Figure 7 down. The total positive impulse corresponds to the characteristic of a blast propagating inside the 25cm width straight street. The experimental results from Rose *et al.* [5] corresponding to the closest configurations have been superposed to the positive impulse experimental variation in Figure 7. They correspond to straight streets of 1.6 m/kg$^{1/3}$ and 4.8 m/kg$^{1/3}$, built with 1.6 m/kg$^{1/3}$ high buildings. As observed for the RP83 detonators, the experimental data and the data from Rose *et al.* are different due to the different position of the sensors and the difference of configuration dimensions. However, a similarity of decrease is observed far from the center of the explosion.

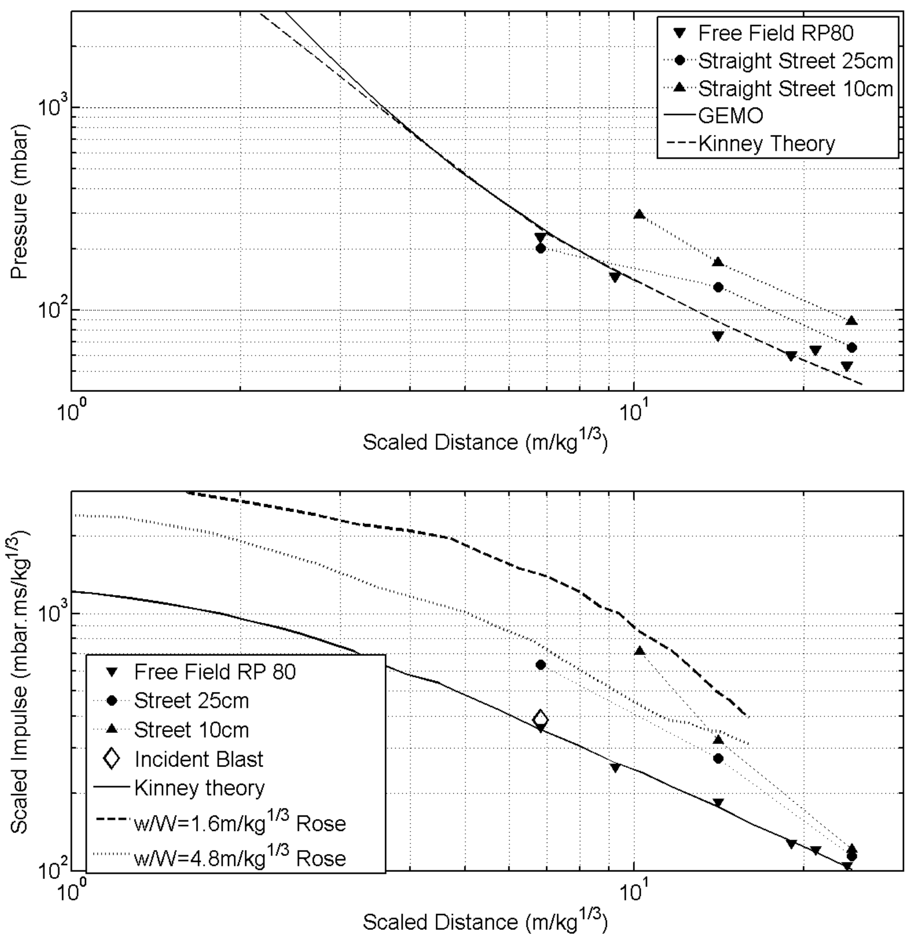


Figure 7 : Impact of the street width on the scaled characteristics variation of a blast produced by a RP80 regarding the scaled distance (up: overpressure peak, down: scaled positive impulse)

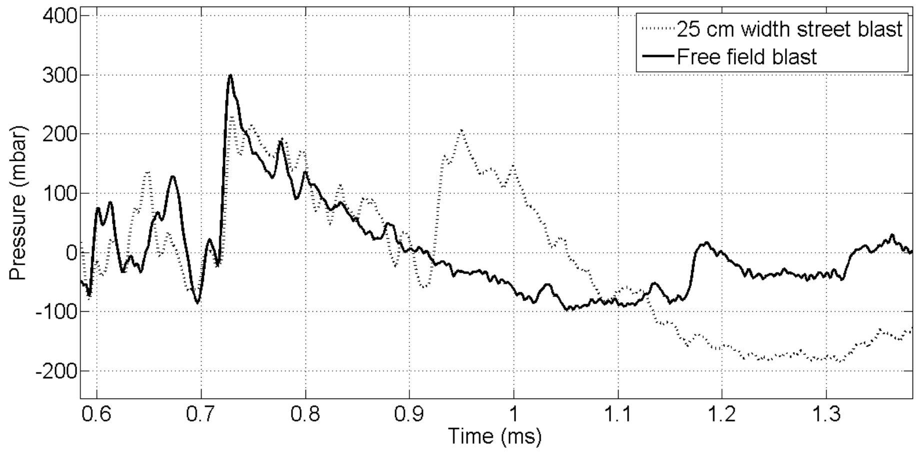


Figure 8: Pressure signal of a blast at 350mm from the explosion of a RP80 in a 25 cm width street and in free-field (C4-200kHz filtered)

Before the merger of the incident blast and the reflected blast, the positive phase of the incident blast is not affected by the confinement and is similar to a blast propagating in free-field. The merger of the incident and reflected waves increases the characteristics of the blast. The time the blasts need to merge depends on the explosion energy: the more powerful the explosive, the faster the merger between the two blasts happens.
The straight street configuration increases the blast characteristics: the characteristics are higher when the blast propagates in narrow streets. While the overpressure is translated to higher values when the street width decreases, the impulse decreases faster in narrow streets.
The comparison of the experimental results with results from Rose *et al.* [5] shows a good coherence with the decrease of the positive scaled impulse regarding the scaled distance.

**Buildings height**

The effect of the building height on the blast propagation is investigated through the configurations 1, 2 and 3 (cf. Figure 3).
Only the results concerning the RP83 detonators are presented here. The blasts from firecrackers and RP80 detonators present similar results and, as a consequence, are not described here.

Figure 9 depicts the variation of the scaled characteristics of the blast generated by a RP83 detonator for different building heights and street widths. A general increase of the overpressure and the scaled positive impulse is observed when the construction height increases. A similar observation was made by Rose *et al.* [5]. The experimental results from the closest configurations to the configurations studied in this paper have been superposed to the experimental variation of the positive impulse (Figure 9). They correspond to two straight streets 2.4 m/kg$^{1/3}$ and 1.6 m/kg$^{1/3}$ large, built with 1.6 m/kg$^{1/3}$ high buildings and one street 1.6 m/kg$^{1/3}$ large and 1.6 m/kg$^{1/3}$ high. As observed in the section focused on the effect of straight streets on the blast propagation, the experimental data and the T.Rose's data are different due to the different position of the sensors (wall of the buildings vs. flush at the ground) and the difference of configuration dimensions. However, a similar decrease is observed for the propagation inside the configuration 3 (10 cm straight street with 20 cm high buildings) and the results of Rose *et al.* [5] for a 1.6 m/kg$^{1/3}$ width straight street with 1.6 m/kg$^{1/3}$ high buildings.

A similar decrease of the scaled positive impulse is observed between the blast propagation inside the configuration 4-Part A (25cm straight street with 10cm buildings) and inside the configuration 3 (10cm straight street with 20cm buildings). While the impulse decreases fast inside the configuration 2 (10cm straight street with 10cm buildings), the decrease inside the configuration 3 is slower and similar to the one inside the configuration 4-PartA. This observation can be explained by the fact that the configuration 2 does not confine enough the blast and the energy of the explosion is lost. In the opposite, the configurations 3 and 4-Part B presents a degree of confinement enough to maintain the energy of the blast inside the street.

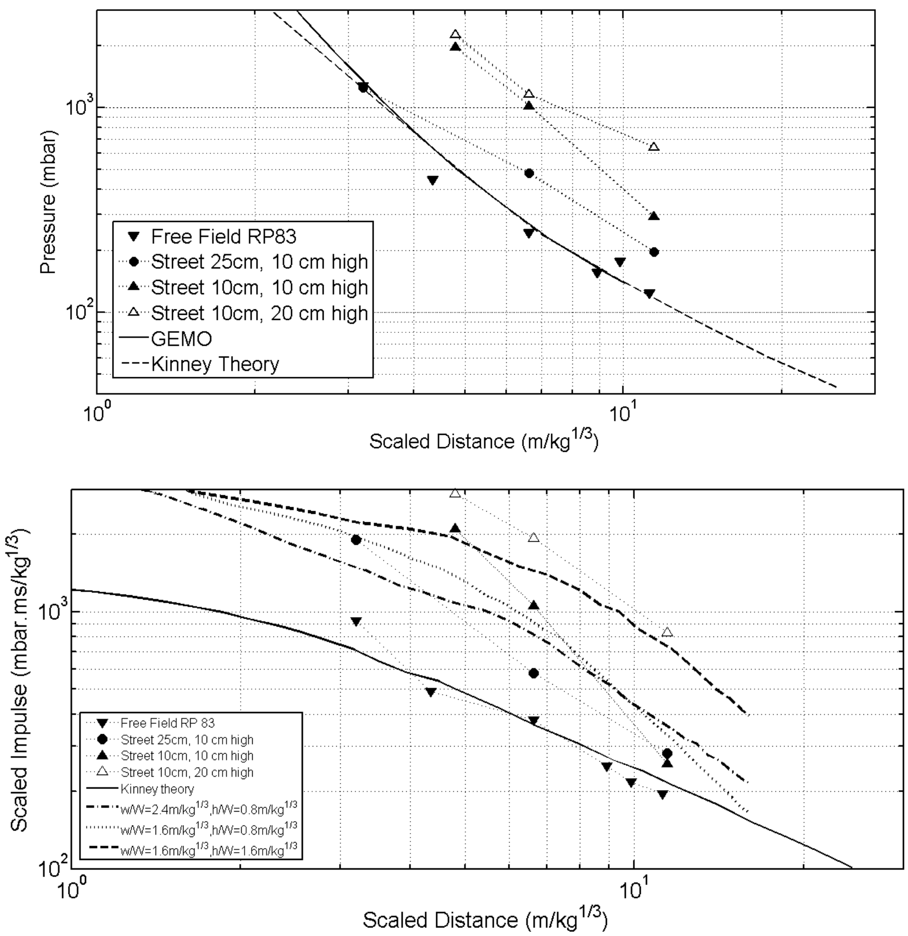


Figure 9: Impact of the street width and building heights on the scaled characteristics variation of a blast produced by a RP83 (up: overpressure peak, down: scaled positive impulse)

The propagation of the blast depends on the street width but also the height of the buildings. When a narrow street is not high enough, the blast positive impulse decreases fast. In the opposite, if the buildings are high enough, the energy of the blast is kept inside the configuration and the impulse decreases as it would do in free-field.

### T-junction

The effect of the T-junction on the blast propagation is investigated through the configurations 1, 4-Part A and 4-Part B (cf. Figure 3). The blasts from a RP80 detonator and a RP83 detonator are described here. The blast generated by a firecracker presents similar results than the one from a RP83 and, as a consequence, is not described here.

Figure 10 depicts the variation of the scaled positive impulse for the different configurations and the two types of detonators. Two matrices of scaled distances are proposed for the T-junction : the first couple of distances, called "T-junction inside" has been estimated supposing that the blast propagates inside the configuration, the other one, called "T-junction direct" has been estimated using the smallest distance from the explosive to the sensor positions, as described in Figure 11.
The positive impulses of blasts generated by a RP80 detonator and a RP83 detonator behave differently. Concerning a blast generated by a RP80 detonator, the variation of the positive impulse inside the T-junction behaves similarly than inside a 25 cm straight street, using the "T-junction inside" scaled distances. The positive impulse of a blast generated by a RP83 has similar values than a blast propagating inside a 25 cm straight street but with direct distances from the explosion. This difference of behavior may be explained by the difference of explosive charge. As the RP83 contains a larger quantity of explosive, the buildings might be not tall enough to contain the blast. By contrast, the RP80 contains less explosive. Therefore, the buildings might be tall enough to contain the blast inside the T-junction. This result confirms the observation of T. Rose *et al.* [5] that concluded that a scaled building of 3.2 $m/kg^{1/3}$ height can be considered to be infinite with respect to the positive phase impulse; buildings lower than 3.2 $m/kg^{1/3}$ don't confine totally the explosion. In the present study, the scaled building heights are equal to 1.94 $m/kg^{1/3}$ for the RP80 detonator and 0.91 $m/kg^{1/3}$ for the RP83 detonator. In both cases, the buildings don't reach the infinite height described by T. Rose *et al.* [5] and then, don't confine perfectly the blast wave. However, the scaled dimensions concerning the RP80 detonator are closer to the infinite dimensions. As a consequence, the confinement of the blast is more important.

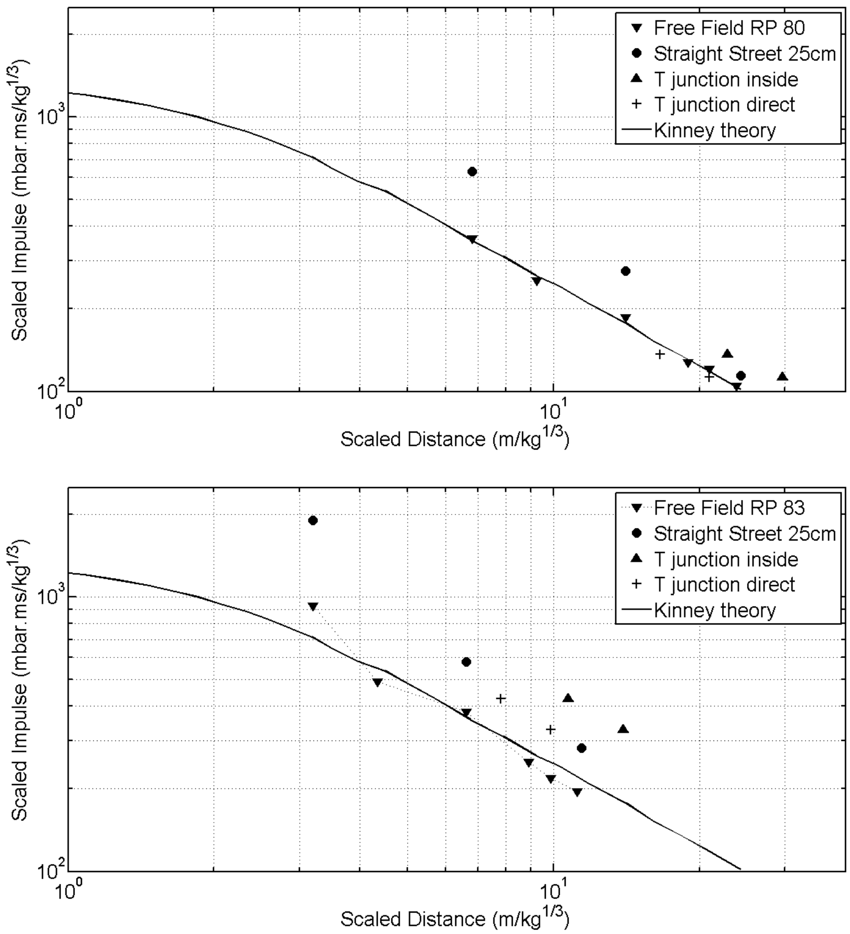


Figure 10: Variation of the scaled positive impulse of a blast generated by a RP80 detonator and a RP83 detonator inside the T-junction

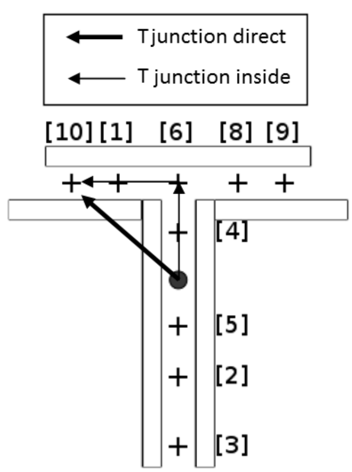


Figure 11: Schematic of the two matrices of distance: "T-junction inside" and "T-junction direct"

Figure 12 depicts the variation of the overpressure peak regarding the scaled distance for the two detonators. As it has been done for the study of the impulse, two scaled distance matrices are proposed: the "T-junction inside" and the "T-junction direct". Whatever the scaled distance matrix used, the overpressure peak is reduced when the blast propagates inside the T-junction. Figure 13 shows the pressure signals of blast propagating inside the T-junction. Before arriving at the T-junction (C4 and C6 signals as shown in Figure 3) the blast is composed of two main peaks of reflection due to the walls of the street. After the T-junction (C8 and C10, Figure 3), the blast amplitude is reduced and its duration is increased due to the several reflections induced by the change of the propagation direction.

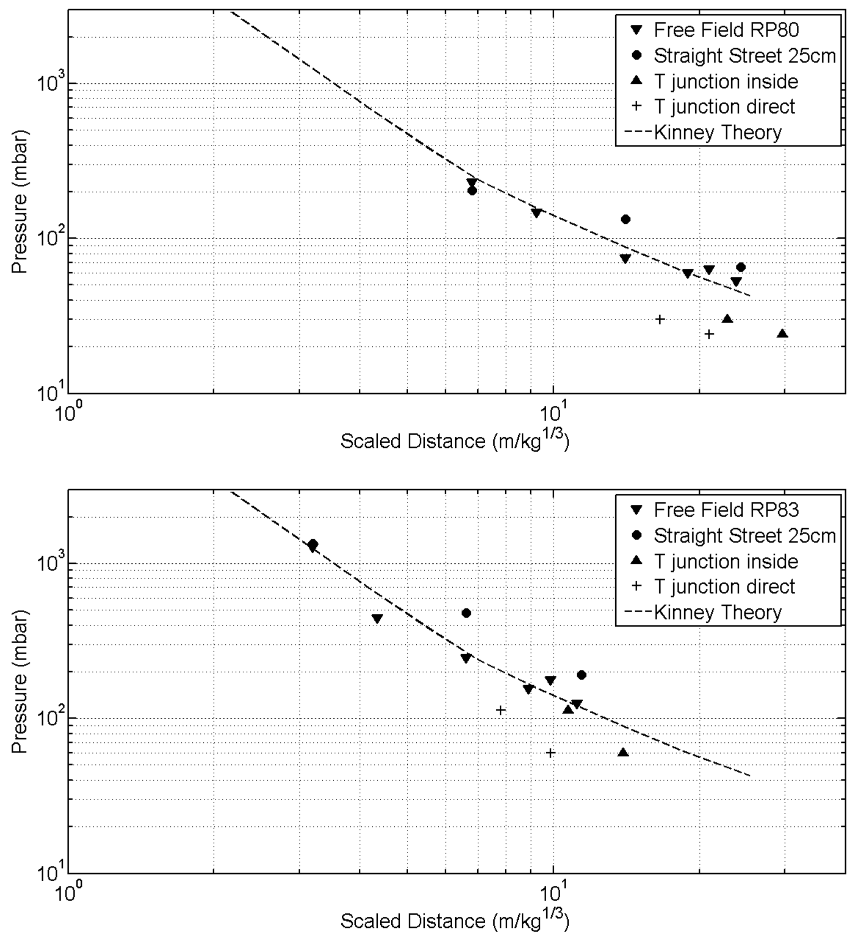


Figure 12: Variation of the overpressure peak of a blast generated by a RP80 detonator and a RP83 detonator inside the T-junction

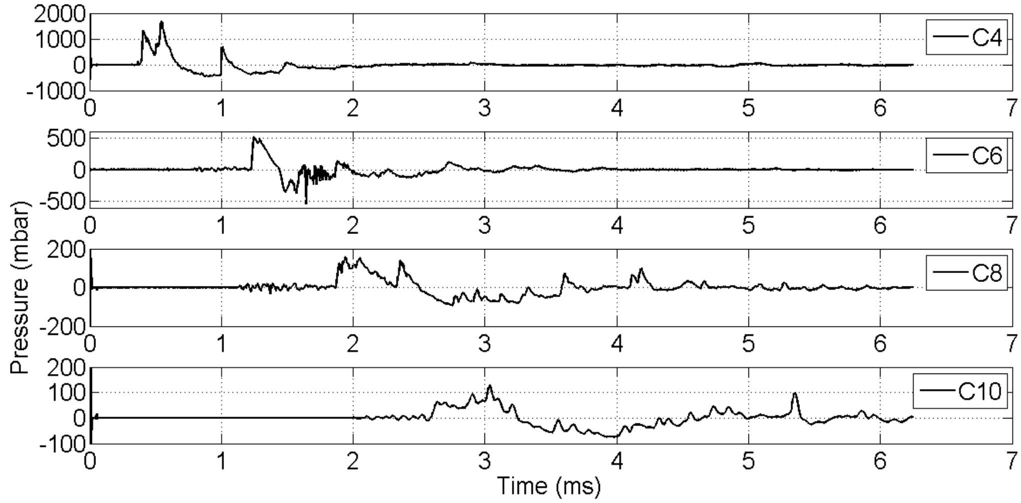


Figure 13: Signals of a blast from a RP83 propagating inside the T-junction (200 kHz filtered) - distance from the center of the explosion: C4: 350 mm, C6: 725 mm, C8: 450mm/C6, inside the T-junction, C10: 800mm/C6 inside the T-junction cf. Figure 3

Figure 14 depicts the scaled arrival time of blast generated by a RP80 and a RP83. As it has been done for the scaled impulse and overpressure, two scaled distance matrices are proposed. The conclusions depend on the type of propagation chosen. If the propagation is supposed totally inside the T-junction, the blast is significantly accelerated by the junction. If the propagation is supposed to be above the buildings, the blast is a little bit slowed down. The reality might be between the two types of propagation studied. The resulting blast may be the result of the addition of a blast wave propagating above the configuration and slowed down by it and a blast wave propagating inside the T-junction.

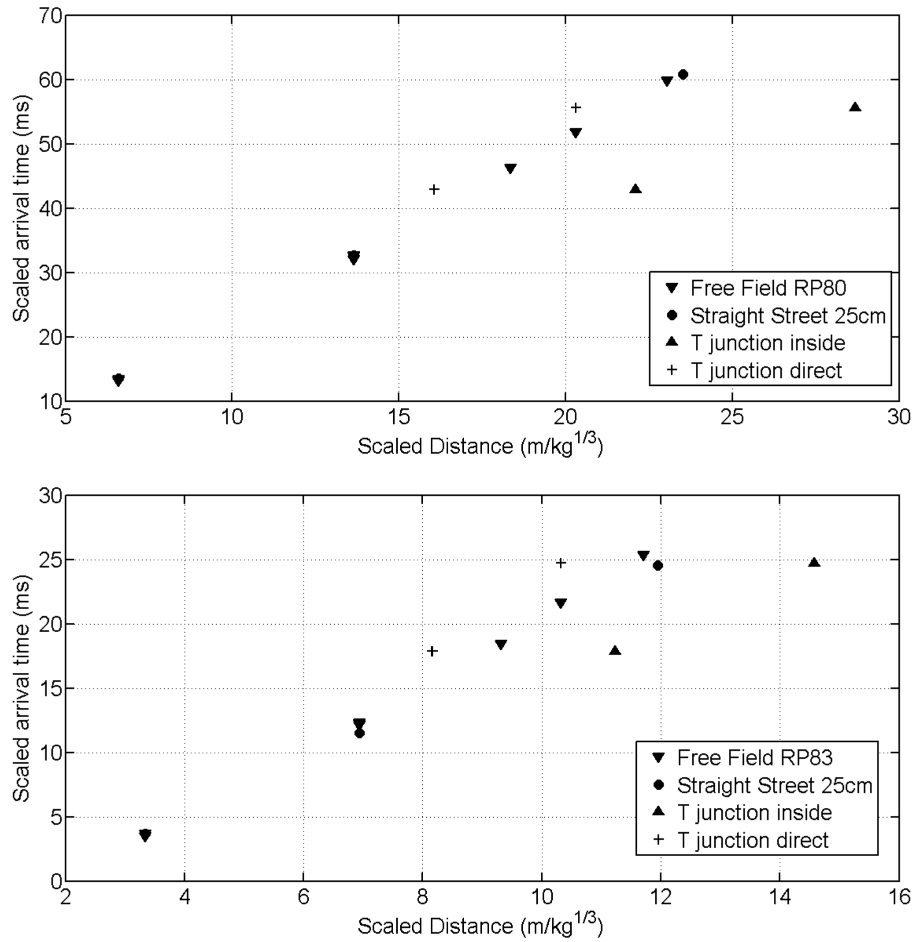


Figure 14: Variation of the scaled arrival time of a blast generated by a RP83 detonator propagating inside the T-junction

The propagation of a blast inside a T-junction is difficult to understand due to the average height of the buildings. The buildings scaled heights for the two detonators are lower than the infinite height described by T. Rose *et al.* [5]. The buildings are not high enough to totally contain the blast and it seems that the blast observed inside the T-junction is the addition of two blasts: one blast propagating inside the configuration and one other propagating above it. However, the configurations simulated in the present project have been designed to fit with a regular city dimensions with buildings of 20 m height, corresponding to 6 or 7 floors buildings. Using infinite height buildings would not represent the reality.

**Cross junction**

The cross junction effect on the blast is studied by comparing the characteristics of blasts propagating inside the configurations 1, 2, 4-part A and 5 (cf. Figure 3).

The Figure 15 depicts the variation of the overpressure and scaled positive impulse of the blasts regarding the scaled distance. Only the results for the RP80 detonator are presented as the blast generated by a firecracker presents the similar results. The blast propagating inside the 25 cm width street of the cross is similar to the one propagating inside a 25 cm width straight street. This observation can be confirmed by the comparison between a blast propagating inside a 25 cm straight street and inside a 25 cm cross street, given in Figure 16. As noticed before, the incident blast is not affected by the cross junction. However, while the incident blast waves are identical, the reflections are impacted by the presence of the junction.

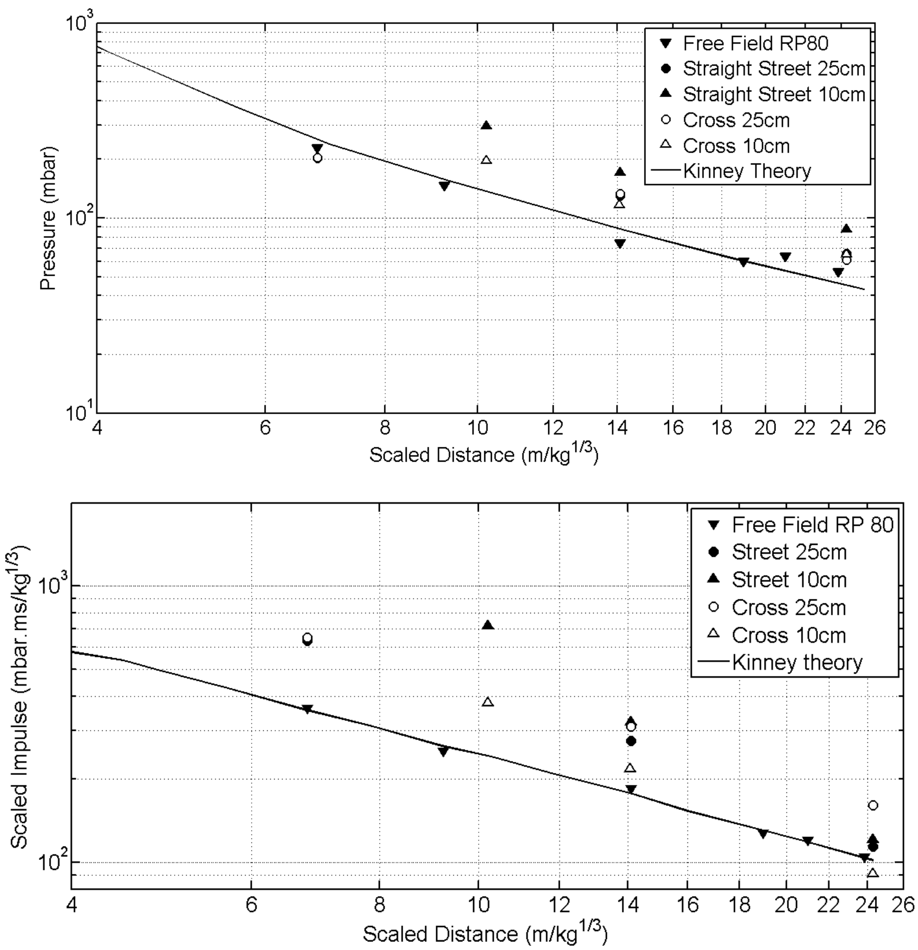


Figure 15: Cross junction effect on blast characteristics (up: overpressure peak, down: scaled positive impulse)

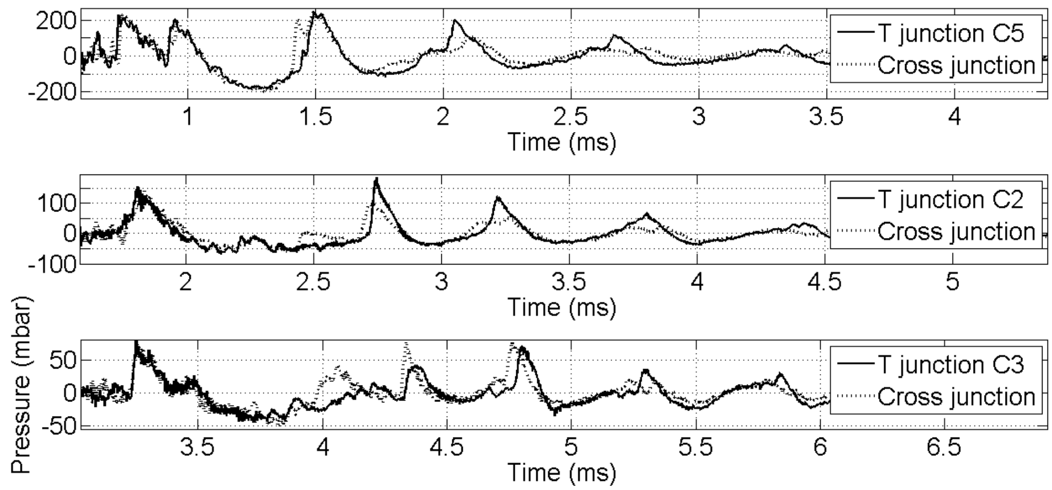


Figure 16: Propagation of a blast inside the 25 cm straight street configuration and the 25 cm cross street (distance from the center of the explosion: C5: 350 mm, C2: 725 mm, C3: 1250 mm) - 200kHz filtered signals.

The characteristics of the blast inside the 10 cm width street of the cross junction are reduced by about 30 % compared to the 10 cm width straight street. The overpressure peaks of the blast inside the 10 cm cross street are close to the ones of the blast inside the 25 cm cross street. However, the positive impulse of the blast inside the 25 cm cross street is higher. This observation can be supported by the blast pressure signals propagating inside the two part of the cross at 1250 mm from the center of the explosion (Figure 17). The maximum levels of pressure are similar for the two signals. However, the duration of the positive phase is larger in the 25 cm cross straight street, inducing a higher positive impulse value.

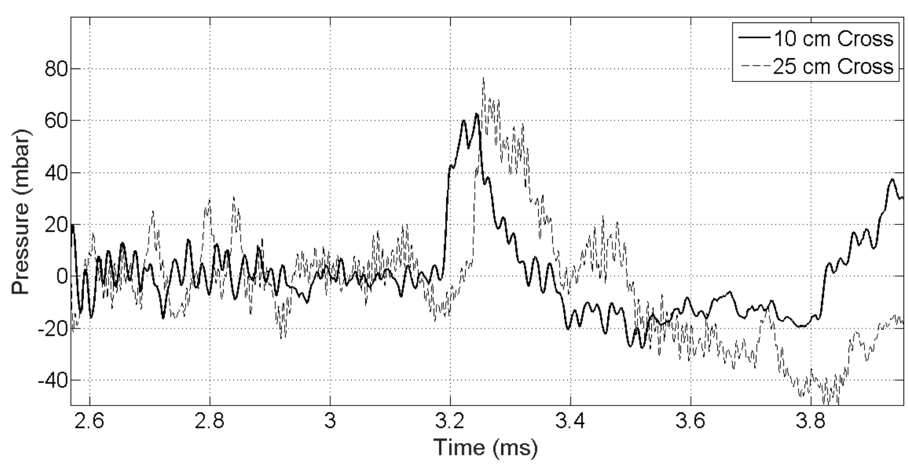


Figure 17: Comparison between the blast propagating inside the 10 cm street and the 25 cm of the cross configuration (sensors C3 and C9, 200 kHz filtered)

The cross junction confines enough the explosion to increase the characteristics of a blast compared to a free-field propagation, as would have done a 25 cm straight street. However, the blast inside the 10 cm straight street is attenuated compared to a propagation inside a 10 cm straight street. This phenomenon can be explained by the distribution of the energy inside the configuration: the 25 cm cross street is the largest street and as a consequence, receives the main part of the energy. By contrast, the 10 cm cross street is less open and will receive much less energy than it would receive in a fully 10 cm straight street.

**Channeling**

The effect of the repetition of buildings, called channeling effect, is studied using the configuration 6 (schematized in Figure 3). The configuration 1 (free-field) is used as a reference.

Figure 18 depicts the variation of the overpressure peak and the scaled positive impulse of a blast propagating inside the studied configurations. The RP80 and the firecracker are represented in the same figure. Between the spaced buildings that decrease the blast characteristics and the confinement that increases them, the blast propagation is similar to a free-field propagation. However, at the exit of the channeling configuration, the blast positive impulse and overpressure are reduced of about 80 % from the free-field values.

On the contrary, the blast propagation speed inside the configuration channeling increases: the blast arrives 0.07 ms earlier than the free-field blast at a given distance (0.1 ms earlier at the end of the propagation). This difference of speed can be visualized in Figure 19, depicting the signals of a blast from a RP80 detonator propagating inside the channeling configuration and in free-field configuration at 725 mm from the explosion.

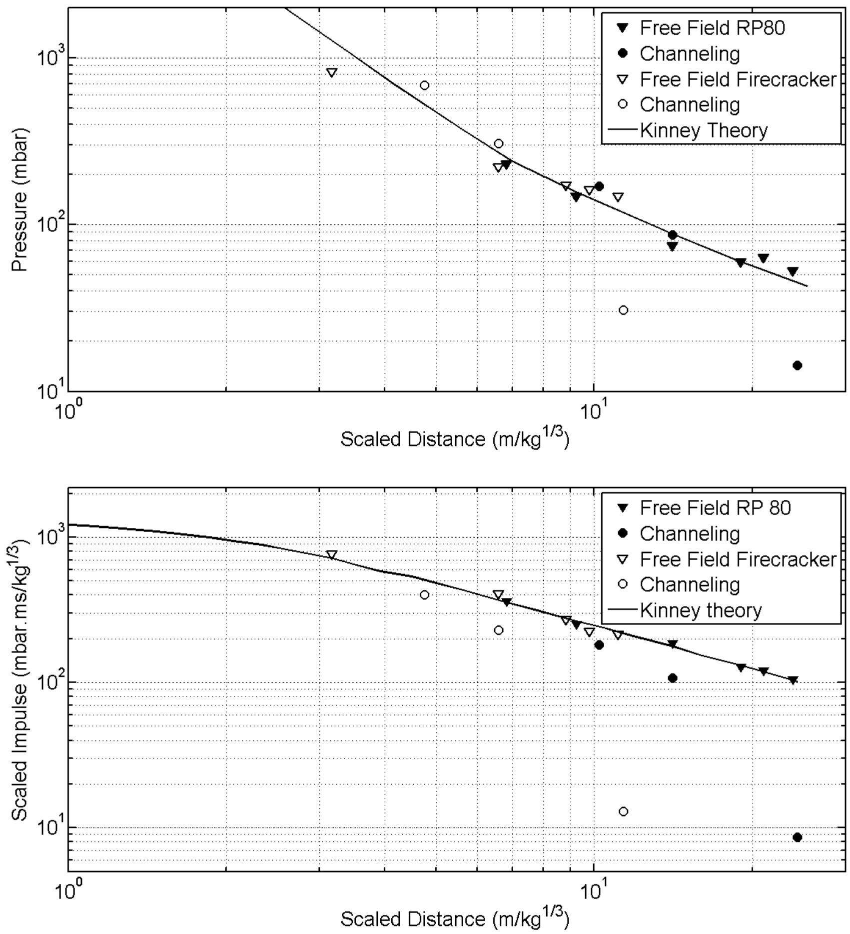


Figure 18: Variation of the overpressure peak and scaled impulse inside and outside the channeling configuration

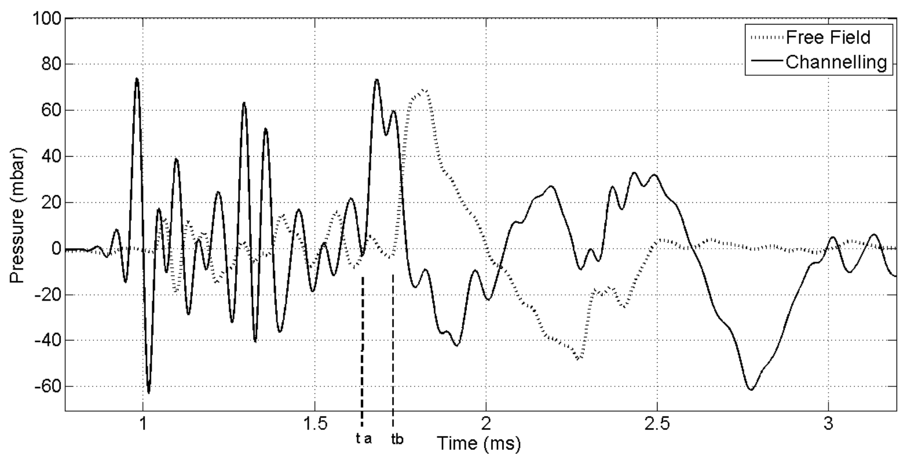


Figure 19: Blast signal in free-field and inside the channeling at 725 mm from the center of the explosion - C8 - 200kHz filtered - RP80 detonator. ta: arrival time of the blast propagating inside the channeling, tb: arrival time of the blast propagating in free-field

Figure 20 depicts the blast signal at 525 mm, 725 mm (inside the channeling) and 1250 mm (outside the channeling) from the explosion of a firecracker. The observations made above can be validated: the amplitude of the blast at the exit of the configuration (C9) is really reduced compared to the one inside the configuration. Several reflection peaks can be observed. The superposition of signals in free-field and inside the configuration at 725 mm confirms the increase of the speed of propagation inside the configuration, as the blast inside the channeling arrives sooner at the sensor at 725 mm from the explosion.

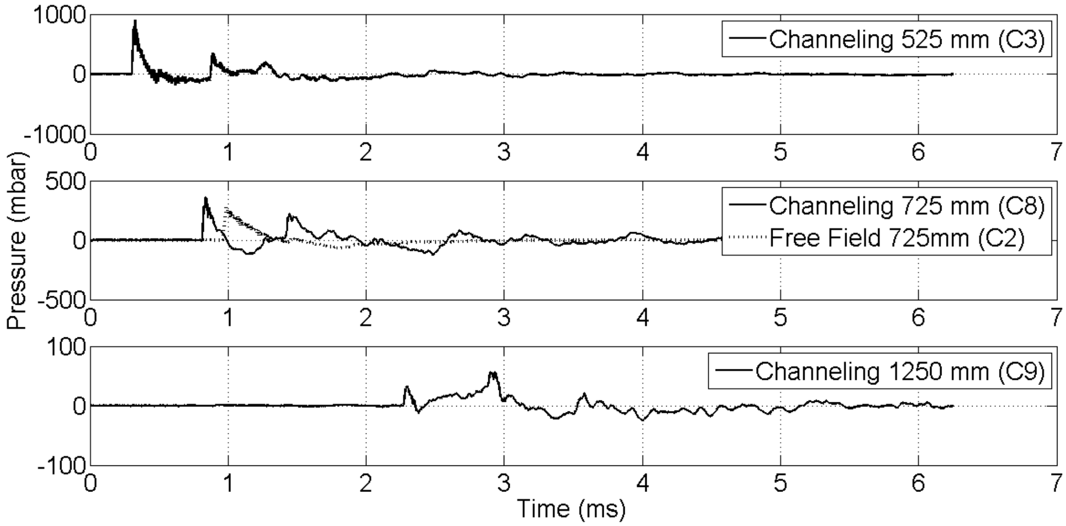


Figure 20: Pressure signal of a blast propagating inside the channeling configuration (distance from the explosion: C3: 525 mm, C8: 725 mm, C10: 1250mm (outside of the channeling configuration) - 200kHz filtered) - firecracker *(The superposition of signals in the channeling configuration and the free-field has been done using the arrival time on a sensor at 350 mm from the explosion, outside of the configuration)*

Between the effect of the confinement and the effect of gaps between buildings, the blast propagating inside a channeling configuration is similar to the one propagating in free-field. However, the blast is accelerated. By contrast, the blast characteristics are highly reduced at the exit of the configuration.

**Scaling law**

The Hopkinson scaling law is a common approach to compare the propagation of a blast produced by a given explosive to another scale [8]. The scaling law assumes that the blast wave generated by an explosion depends only on the energy released and the medium of propagation. As a consequence, two explosives with the same geometry, containing the same compound but with different quantities will generate a comparable blast. Then, whatever the mass of explosives, there is a conservation of the scaled characteristics of the blast propagating in the same medium:

$$\lambda = \frac{R_{exp}}{\sqrt[3]{m_{exp}}}$$

$$I_s = \frac{I_{exp}}{\sqrt[3]{m_{exp}}}$$
$$\Delta P = \Delta P_{exp}$$

with $R_{exp}$ the distance from the explosive, λ the scaled distance, $m_{exp}$ the explosive mass, $I_s$ the scaled impulse and ΔP the overpressure.

The Figure 21 depicts the Hopkinson law applied on straight street configurations. Dashed lines have been added to help the reading of the graphs. The scaled characteristics of blasts generated by the two detonators and propagating in free-field are fitting, confirming the coherence of the law for free-field blast propagation. The characteristics of blasts propagating inside straight streets depict also a good fitting, most particularly for the 25 cm straight street for the positive scaled impulse. The differences that appear are mainly due to the difference of scaled dimensions. When the street gets narrow, the Hopkinson law cannot be applied anymore.

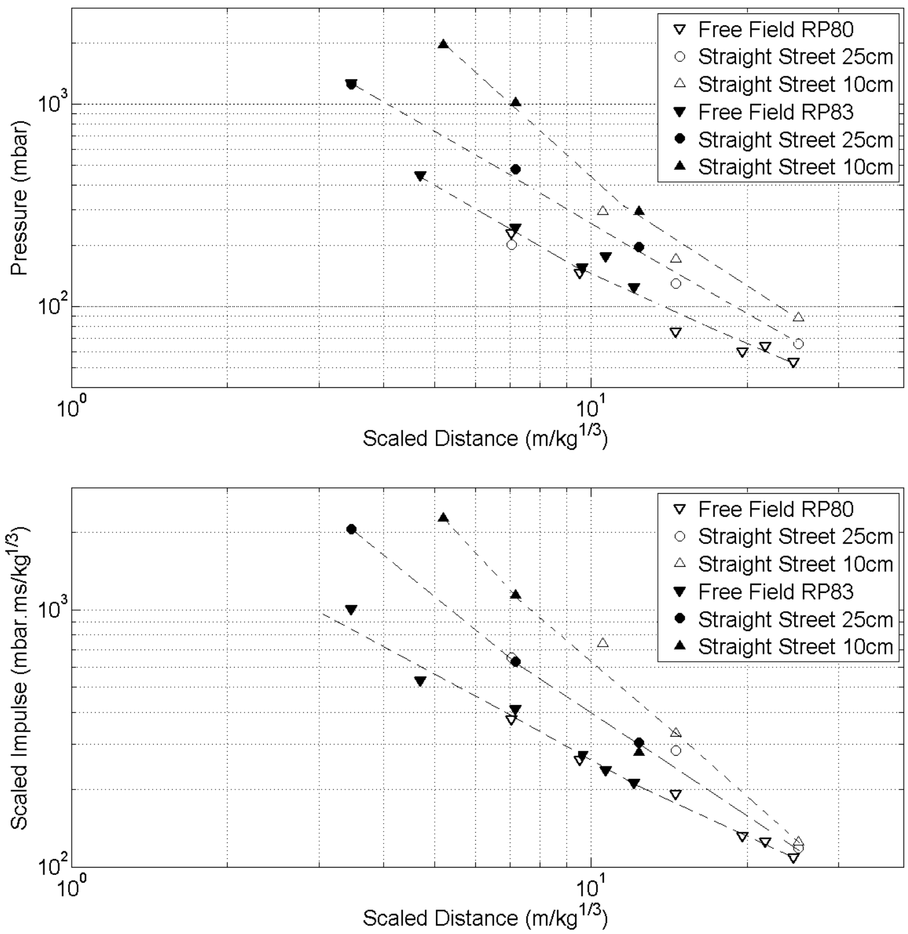


Figure 21: Hopkinson law applied to straight street (up: overpressure peak, down: scaled positive impulse)

## Conclusions

The objective of this study is to gain an understanding of blast propagation in an urban environment at laboratory scale. Five typical urban configurations have been tested: the free-field, the straight street, the T-junction, the cross-junction and the channeling. Three types of explosives have been used: the firecracker, the RP80 detonator, and the RP83 detonator.

The analysis of the free-field brings information about the repeatability, the geometry and the TNT equivalent of each explosive. It appears that the firecracker shows similar results than the RP83 but with a lower repeatability.
Studies about the straight street configuration show an increase of the blast characteristics when the street is narrow. The propagation inside the T-junction is difficult to analyze due to the height of buildings: the buildings might not be high enough to contain perfectly the blast, inducing a propagating over the configuration. The larger street of the cross-junction acts like a straight street with the same width, increasing the characteristics of the blast. By contrast, the narrow street of the cross-junction receives much less energy that it would receive in a full straight street with the same dimensions. As a consequence, the characteristics of the blast propagating inside the small street are much smaller than the ones inside a 10 cm straight street. Concerning the channeling effect, between the confinement of the buildings and the gaps between them, the blast propagating inside the configuration is similar to a blast in free-field. However, a reduction of about 80 % of the characteristics is observed at the exit of the configuration.

The Hopkinson law has been tested for the straight street configuration. The law is confirmed for the free-field configuration and shows a good coherence for the straight street configurations. However, the difference between the two masses of explosive increases when the street width decreases. This is explained by the difference of the scaled dimensions of the configuration.

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